THz RADIATION SOURCE THROUGH PERIODICALLY MODULATED STRUCTURES

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We have concentrated our activities in the present period to demonstrate the generation of a plasmon instability which could lead to coherent plasmon oscillations in quantum well structures due to population inversion in the carrier distribution. Population inversion is needed to develop the plasma instability. We use a concept where the inversion is achieved by using an energetically selective extraction and injection of carriers into a confined active region consisting of a combination of quantum wells.

We have designed, build, and characterised a first generation of structures which show some first evidence for plasma instability. The measured I-V characteristics confirm the high quality of these samples and cannot be explained consistently with a transfer matrix calculation. We find that deviations from the expected tunnelling behaviour are found close to the condition of population inversion in the carrier distribution in sample g301. Weak THz emission is observed which might have its origin in a plasma instability process. However at present we cannot distinguish the emission process from radiative subband transitions.

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Plasmon instability in double quantum well structures

We have concentrated our activities in the present period to demonstrate the generation of a plasmon instability which could lead to coherent plasmon oscillations in quantum well structures due to population inversion in the carrier distribution. Population inversion is needed to develop the plasma instability. We use a concept where the inversion is achieved by using an energetically selective extraction and injection of carriers into a confined active region consisting of a combination of quantum wells.

The molecular beam epitaxial grown (MBE) structures consist of two quantum wells: the first quantum well (active region) acts as a plasma resonator, which can sustain growing plasma oscillations, and the second quantum well (plasmon emitter) provides a proper arrangement of levels (subbands) to assure efficient emission of plasmons into the resonator. A resonant tunneling diode (RTD) filter, which assures an efficient carrier extraction from the active region, is attached to the plasmon emitter well. Fig.1 shows the band structure of a typical device used in our experiments. This scheme has been designed together with the Boston College group (Prof. Bakshi and Prof. Kempa).

A three level scheme is used to realize a plasmon emitter. The first subband and the third and higher subbands are occupied, while the intermediate second subband is kept at a lower occupation. The occupation of the third subband and higher subbands is maintained by a "heavy" inflow of carriers from the left side which acts as an injector. A high occupation of the first subband is assured by the very fast inter-subband transitions due to emission of LO phonons from the upper subbands (the energy separation between the third and first subband is larger than $\hbar\omega_{LO}$). The second subband is kept partially empty by aligning this subband with the RTD resonance (by applying a proper bias). The population is significantly reduced due to "heavy" carrier extraction.

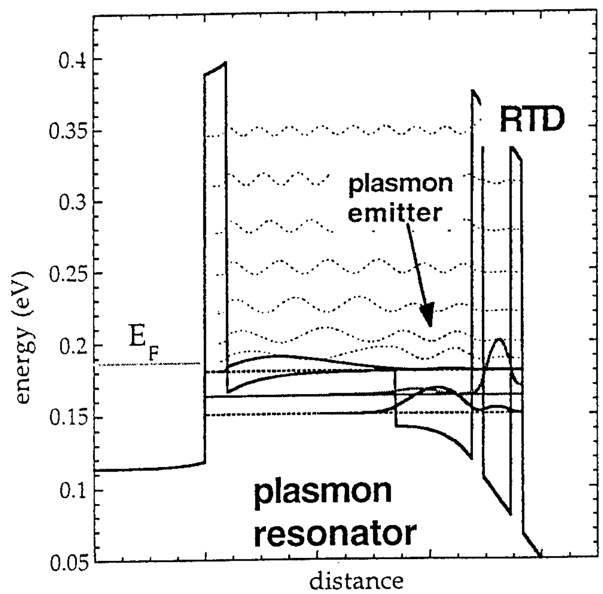

Figure 1: Schematic band diagram of the double quantum well structure consisting of a plasmon emitter, plasmon resonator, and a tunneling diode filter under bias conditions.

Two types of AlGaAs growth techniques are employed to produce the structures: in one structure the Al content is varied by controlling the temperature of the Al source (sample g206), in the other structure digital growth of AlAs is used to change the bandstructure (sample g205, g301). Subsequently, mesa structures of different diameters (from 100 μm to 2 μm) were fabricated using standard RIE etching techniques. Ohmic contacts were formed using an

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AuGe/Ni alloy. In order to establish contacts to the top of the subµm mesas a Si_3N_4 isolation is used to isolate the extended bonding pads to the underlying highly doped GaAs contact layers.

A detailed systematic study of the current-voltage characteristics was performed in order to characterize the structures and to verify their desired properties. The I-V characteristics were measured at 4.2 K using an HP parameter analyzer.

Fig.2 shows current-voltage and conductance-voltage characteristics of two samples g205 and g206, measured on large mesas with a 30µm diameter, representing the two different technological realizations of the designed structure shown in Fig.1. The dI/dV curves show a series of peaks for negative bias (more pronounced for g205), and a single feature for positive bias at ~0.35V. It is verified that the current scales proportional to the mesa area in both samples by investigating several mesa sizes. Fig. 2 also suggest that the digital growth leads to better quality samples, which is evident from more pronounced features in dI/dV. This investigation to improve the sample quality is very important since it will be crucial whether the gain in the sample due to the instability will be high enough to overcome the losses.

The experimental results were compared with two different calculations: the RPA method, which includes screening effects on the transport across the structure, describes the situation better for confined quantum well structures in which one can identify a current limiting bottle neck (RTD in our structures). The second calculation employs the transfer matrix method for the calculation of the transmission coefficient. This method essentially integrates the transmission coefficient of a given structure over all available subband energies. The results with this second method are compared in Fig. 3 for sample g301: the dashed line shows the calculation, the solid line the experiment. The calculated dI/dU characteristic is in qualitative agreement with the experimental curve, except that the calculated features are more pronounced. Part of this resonance broadening is caused by electron-electron scattering processes, which are incompletely treated in our calculation.

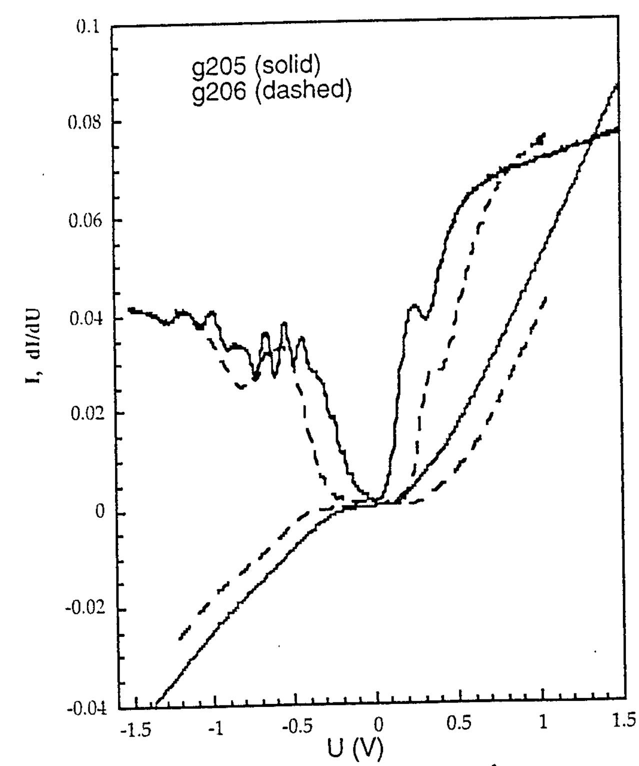

Figure 2: Current (conductance) versus voltage characteristics for two different grown samples.

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The series of peaks for negative bias represent the resonantly enhanced transport as the RTD level tunes through the levels of the active region as a function of bias. For positive bias there is only one distinct feature (around 0.15 V bias). This feature corresponds to the RTD extraction from the localized subbands of the plasmon emitter. This is the bias condition at which an instability is expected to occur. There is also a significantly larger difference between the calculation and the experiment indicating that tunneling might not be the only mechanism responsible for the observed feature. It is also remarkable that this feature is less sample quality dependent than the tunneling structures on the negative bias side.

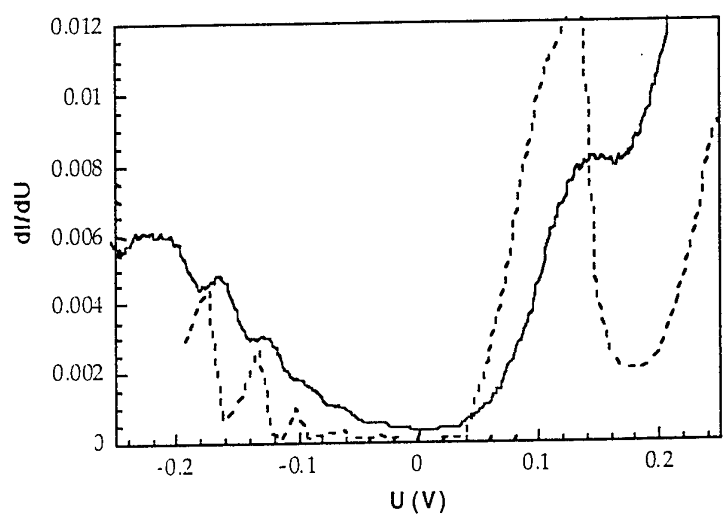

Figure 3: Conductance versus voltage for the sample g301 (solid line) compared to a calculation based on the standard tunneling method (dashed line).

The ultimate goal which we want to achieve with these structures is the generation of electromagnetic radiation in the THz range resulting from the induced plasma instability. One of the key requirements for this instability to occur is a smaller population in the second intermediate sub-band of the plasmon emitter (g_2) in respect to the higher and lower close lying subbands. The population in each subband depends on a dynamic interplay between various transitions and injection-extraction rates. Using the assumption that the third and higher levels are always filled by direct carrier "flooding" from the injector area in our structures, and that the first subband is fully occupied by carriers recombining from the upper subbands into the first one, with the emission of LO phonons these two level can have a high average population. Since the separation between the third and second level is lower than the optical phonon energy we assume that the second subband is not populated significantly by LO phonon emission. Under these circumstances the population of the second subband is determined by the interplay between the rates, Γ_{in}, of scattering into the second subband from all the other subbands, and the rate of escape, Γ_{out}, of carriers from the second subband through the RTD. We find for the structure g301 (assuming g_i=1 for i=1,3) that for a population ratio of g_2=0.3 the required extraction rate has to be in energy terms Γ_{out}=4.9 meV. This scenario should lead to a robust instability with a gain factor of g=1.2 meV.

To complete the population analysis, a calculation of the extraction rate through RTD is necessary. We have obtained this rate by calculating the transmission coefficient across the RTD using the transfer matrix method. From the half-width at half peak height we estimate Γ_{out} as >10 meV, which is well above the value required to obtain a population of g_2=0.3. Therefore

even smaller values of g_2 might be expected. From this we can estimate for structure g301 a growth factor in the order of 1 to 2 meV, which is large enough to develop an instability. The observed feature in the IV curve (Fig.3) could be due to the presence of a plasma instability. However the tunneling resonance of the RTD leads basically to the same feature. Therefore we have to investigate other features which give us confidence that we might have observed a plasma instability. As the feature on the right side of the IV curve is less dependent on the sample quality than the left side which is due to tunneling resonance's we believe to observe the first evidence for the presence of the plasma instability.

We have also performed first emission experiments on these structures and have observed a weak emission signal with a spectral content in the 10 to 15 meV range. This spectral range correspond the energy separation between the third and second subband and could result from radiative subband transitions. The plasmon frequency for these structures is in the same spectral range. From this experiment we cannot draw a conclusive interpretation since the emission signal is very weak in the order of 10^{-10} Watt for one small mesa (3μm). At present we are trying to assemble an array of mesas to increase the signal and to study in detail the current and field dependence which might allow us to identify the process leading to the negative differential resistance and to the emission.

We have designed, build, and characterised a first generation of structures which show some first evidence for plasma instability. The measured I-V characteristics confirm the high quality of these samples and cannot be explained consistently with a transfer matrix calculation. We find that deviations from the expected tunnelling behaviour are found close to the condition of population inversion in the carrier distribution in sample g301. Weak THz emission is observed which might have its origin in a plasma instability process. However at present we cannot distinguish the emission process from radiative subband transitions.